

# Modeling High-Energy Emission from Pulsar Magnetospheres

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Collaborators:

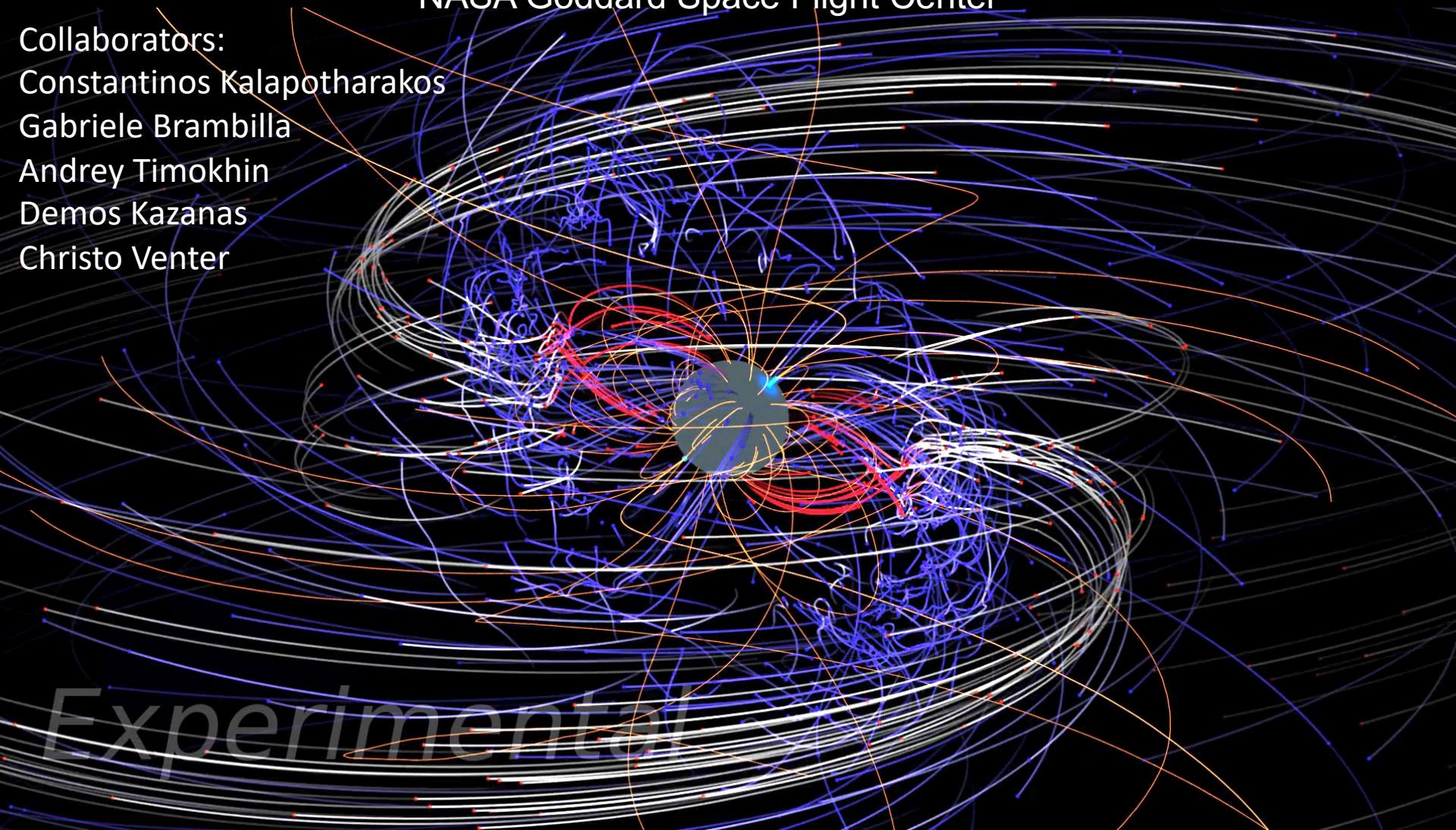
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Andrey Timokhin

Demos Kazanas

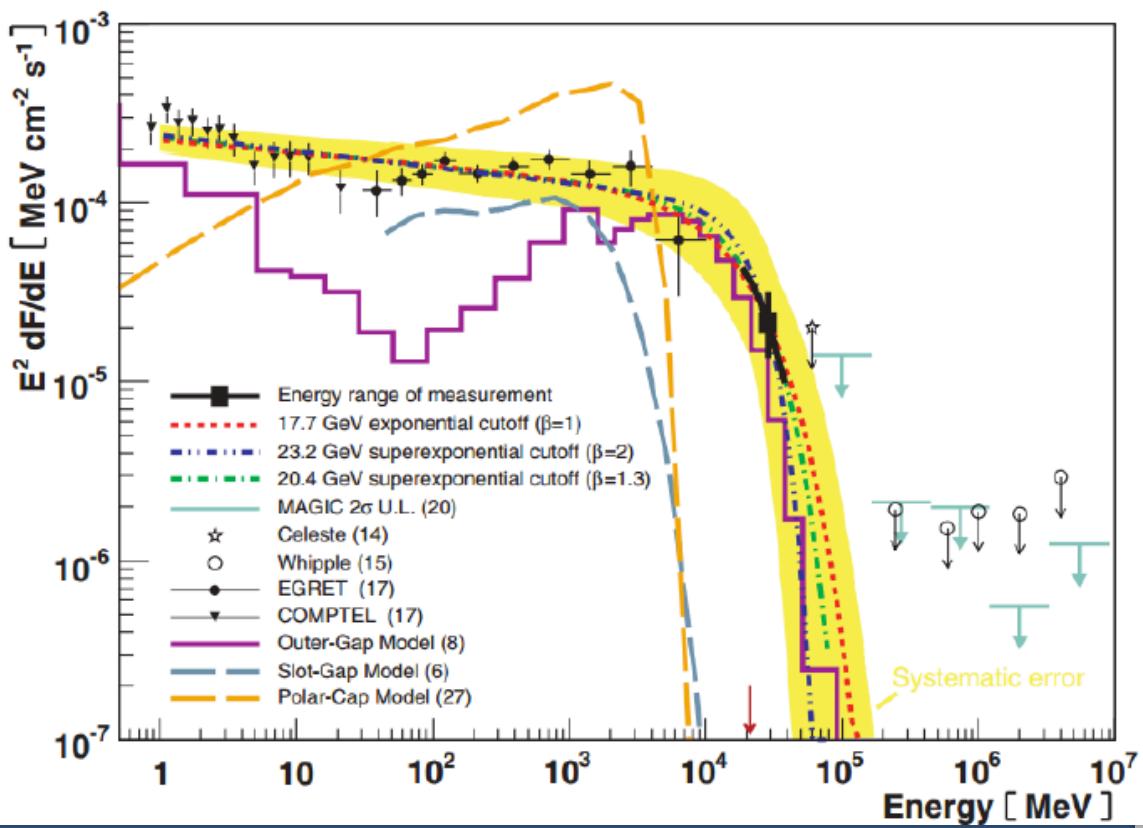
Christo Venter



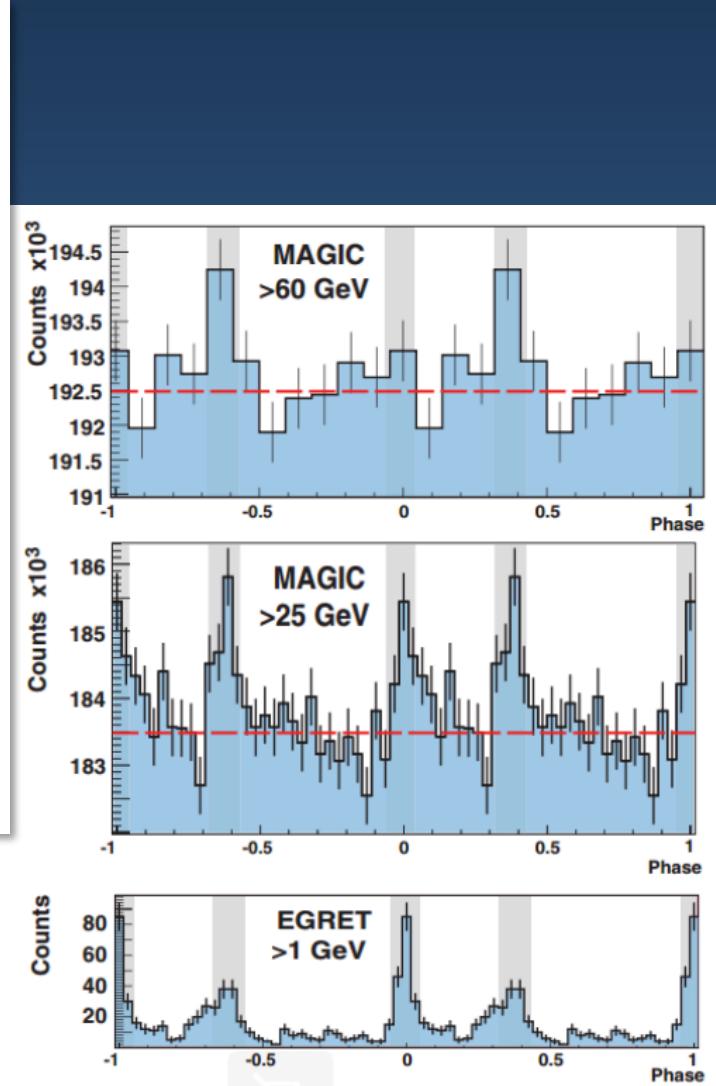
Experimental

# MAGIC detection of Crab pulsar

> 25 GeV (Aliu et al. 2008)



Outer gap model (curvature radiation)  
favored

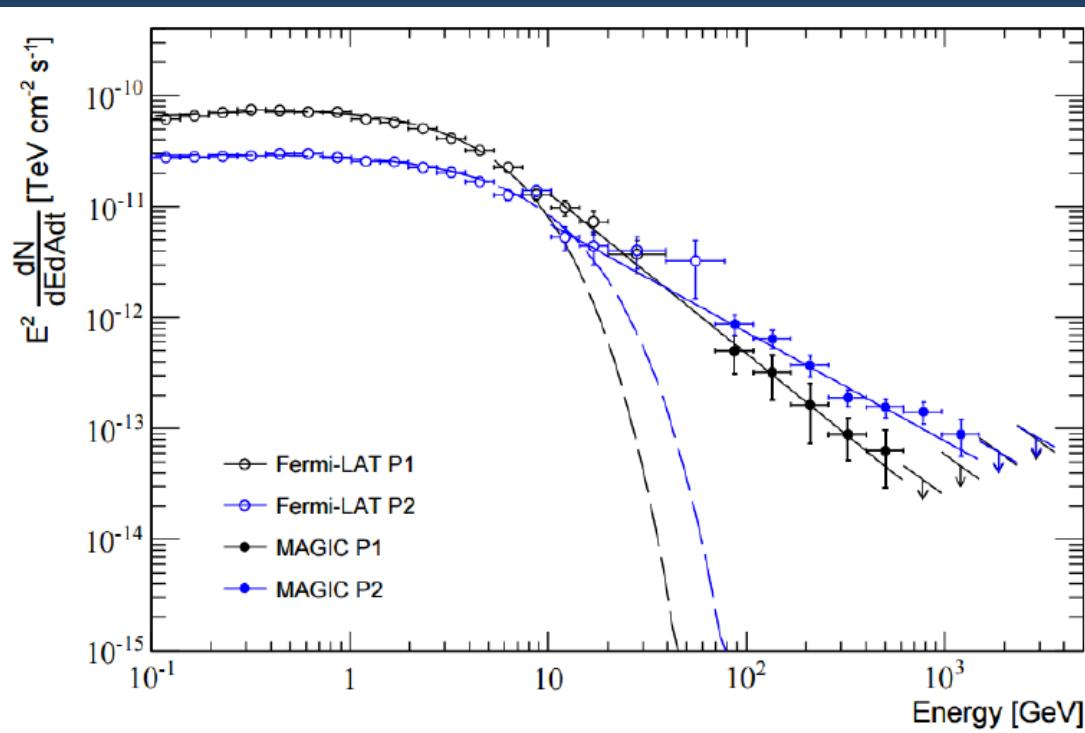


# Detection of Crab pulsar up to 1 TeV

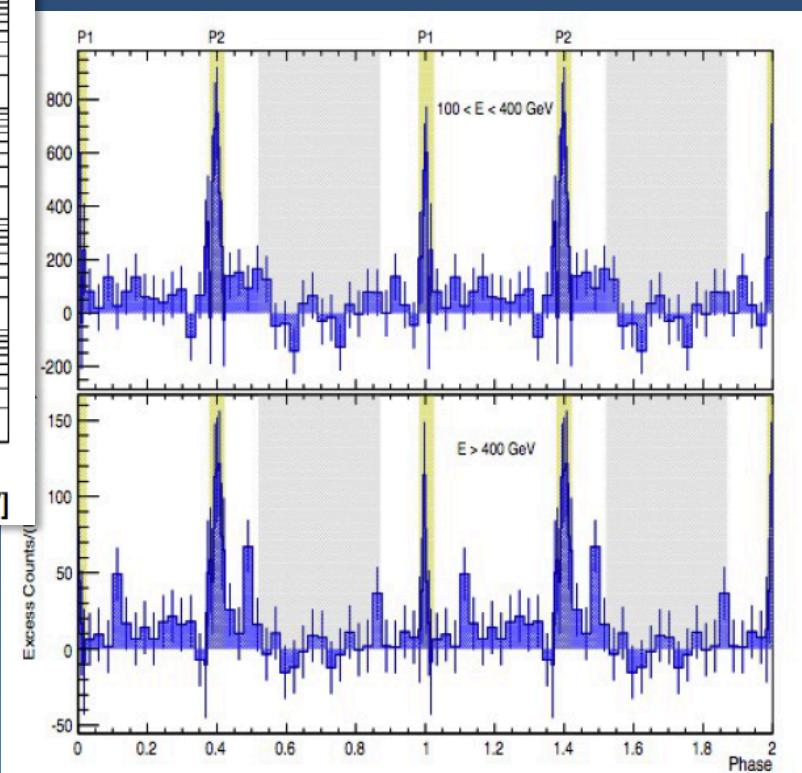
MAGIC - Aliu et al. 2008, 2011

Veritas - Aleksic et al. 2011

MAGIC 40 GeV – 1 TeV (Ansoldi et al. 2016)

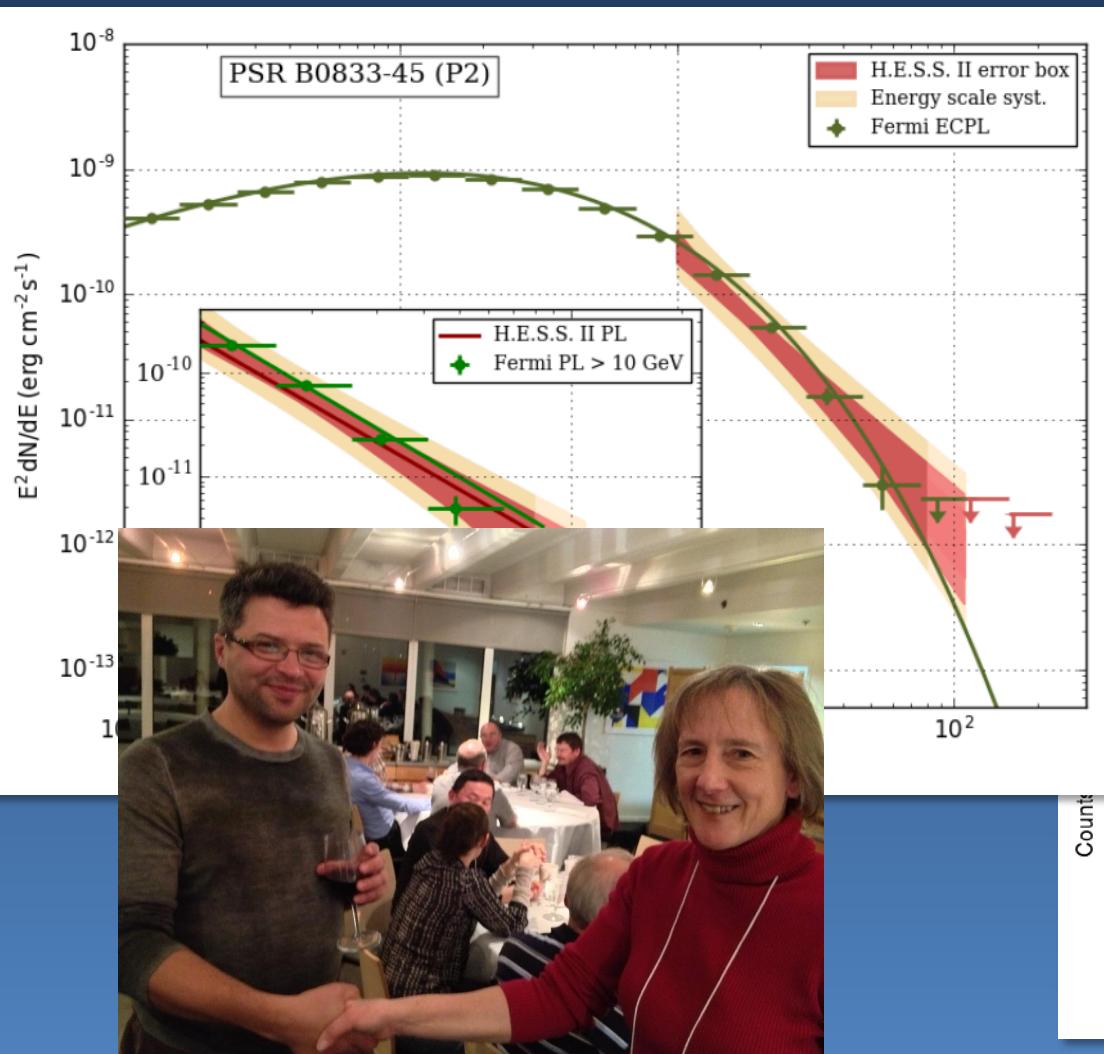


Both peaks still detected!



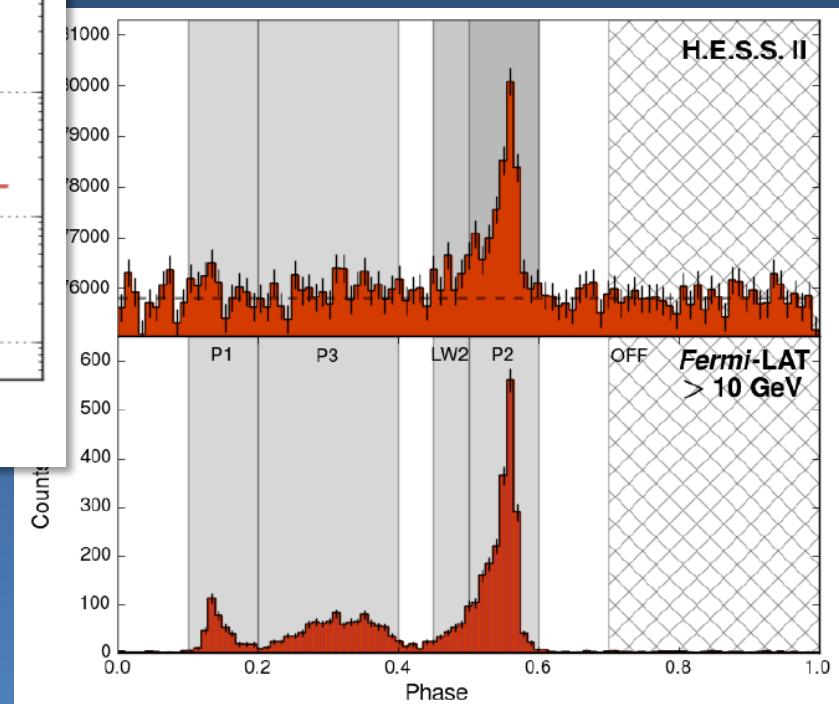
# Vela pulsar – HESS II

10 – 80 GeV (Djannati-Atai 2018)



Continuation of Fermi spectrum (curved sub-exponential) or power law?

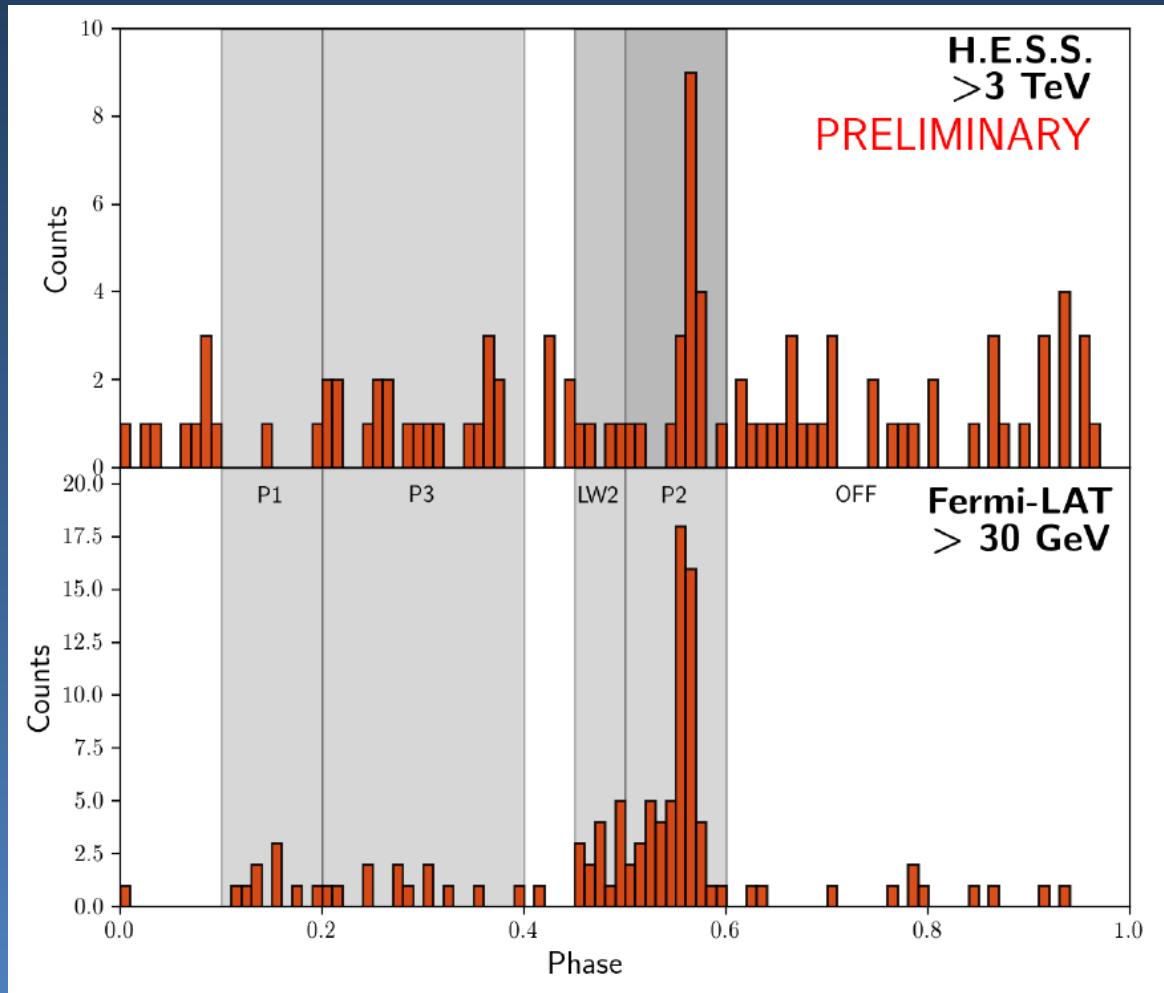
Curvature favored by HESS II at  $> 3.0\sigma$



# Vela pulsar – HESS II

2004 – 2016: 60 hours in stereoscopic mode

3 - > 7 TeV!!  $5.6\sigma$  (Djannati-Atai 2018)



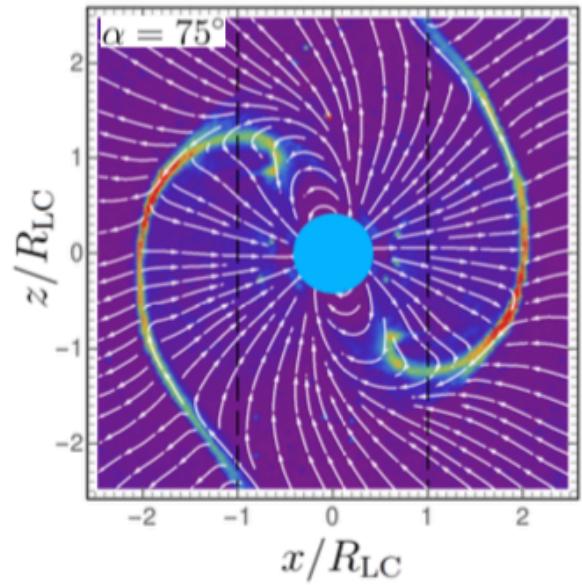
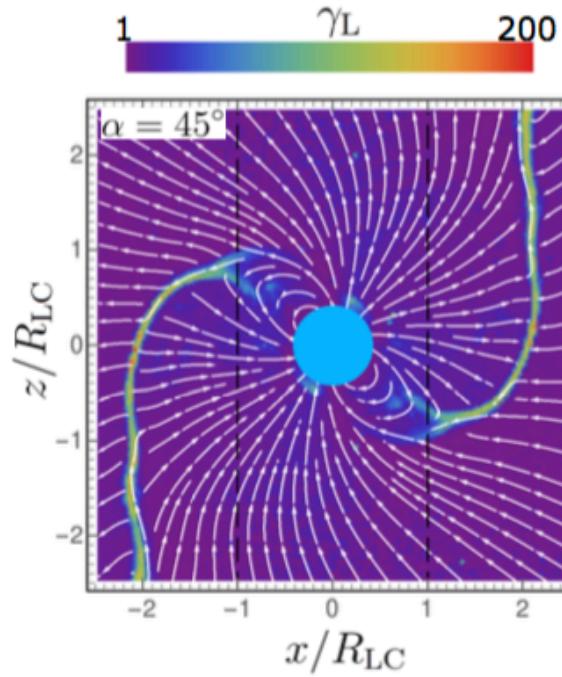
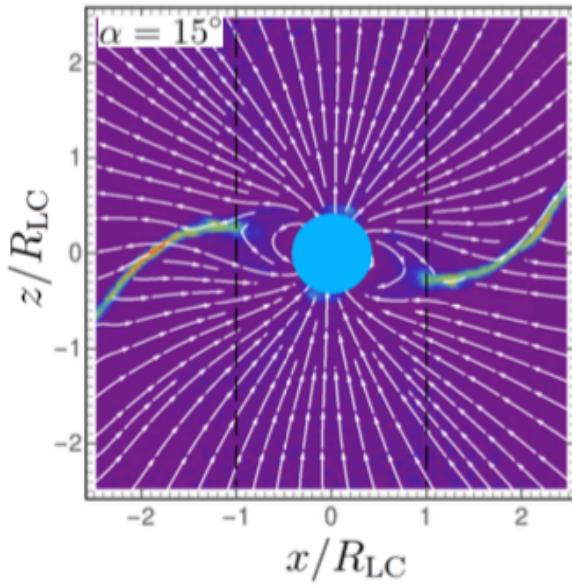
Additional component distinct from GeV spectrum?

# PIC models - acceleration

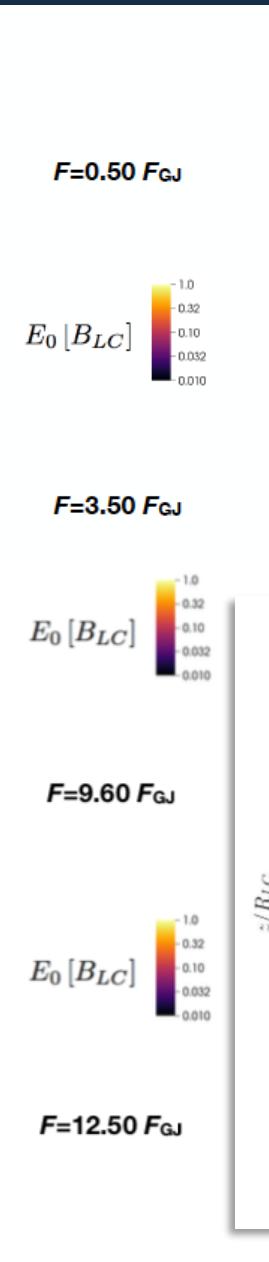
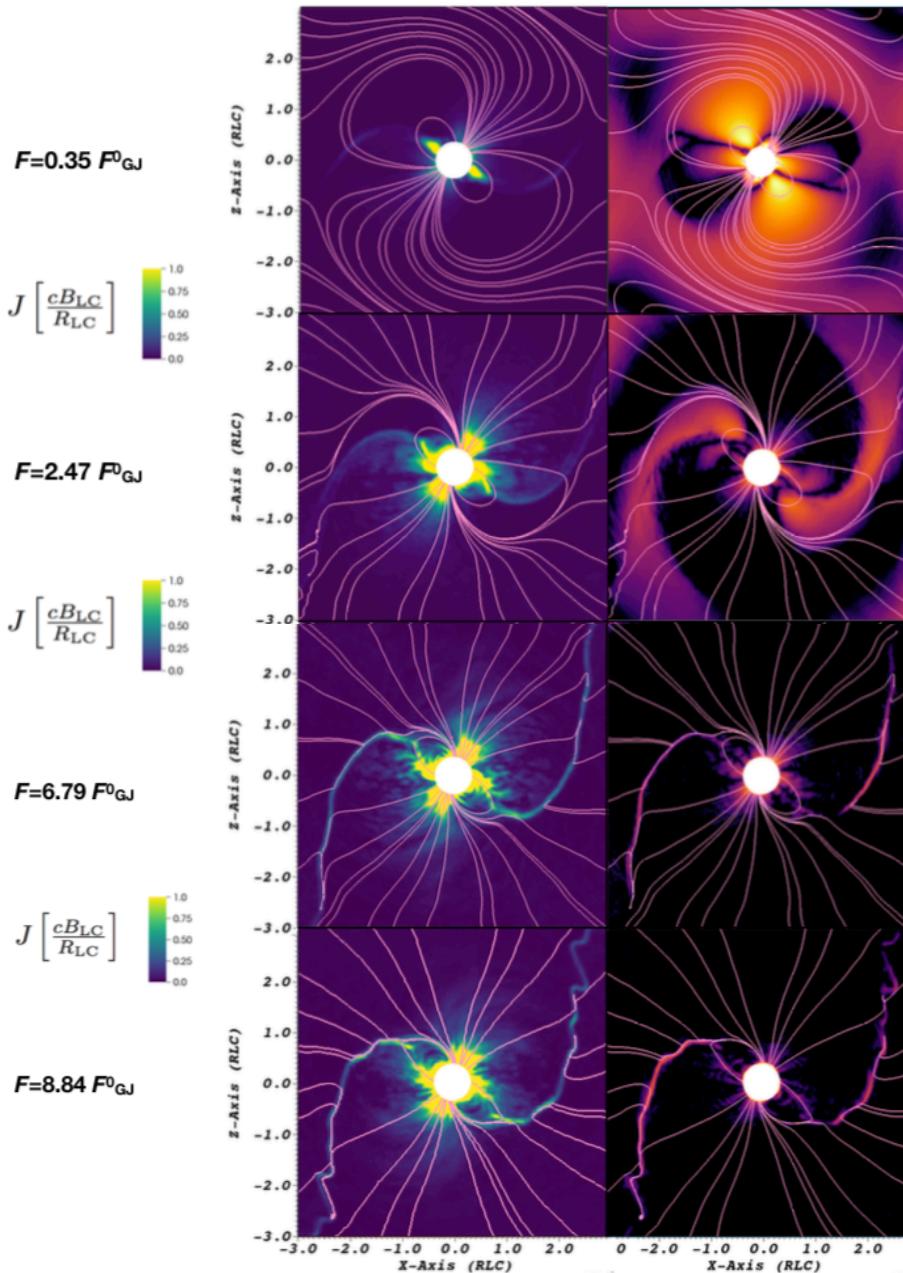
Global particle-in-cell simulations (Kalapotharakos+ 2018)

Most particle acceleration occurs in and near the current sheet and separatrices

$$\mathcal{F} = 28\mathcal{F}_{\text{GJ}}^0$$

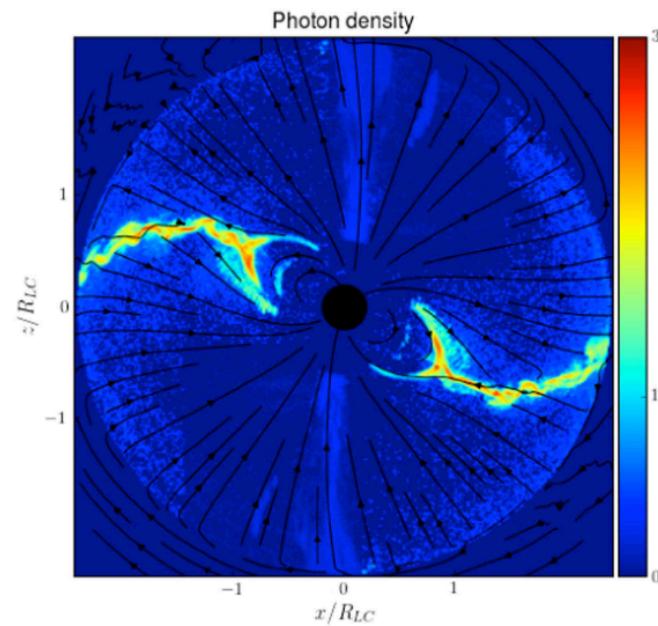


# Current and $E_0$ with injection rate



Brambilla et al. 2018

As pair injection rate increases – region of accelerating electric field shrinks to current sheet

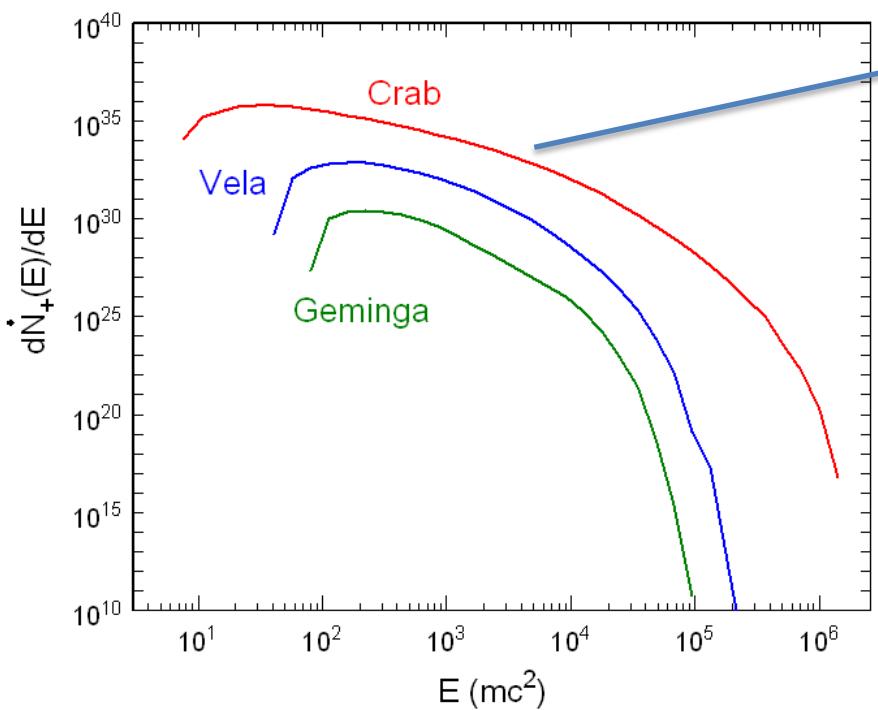


Philippov & Spitkovsky 2018

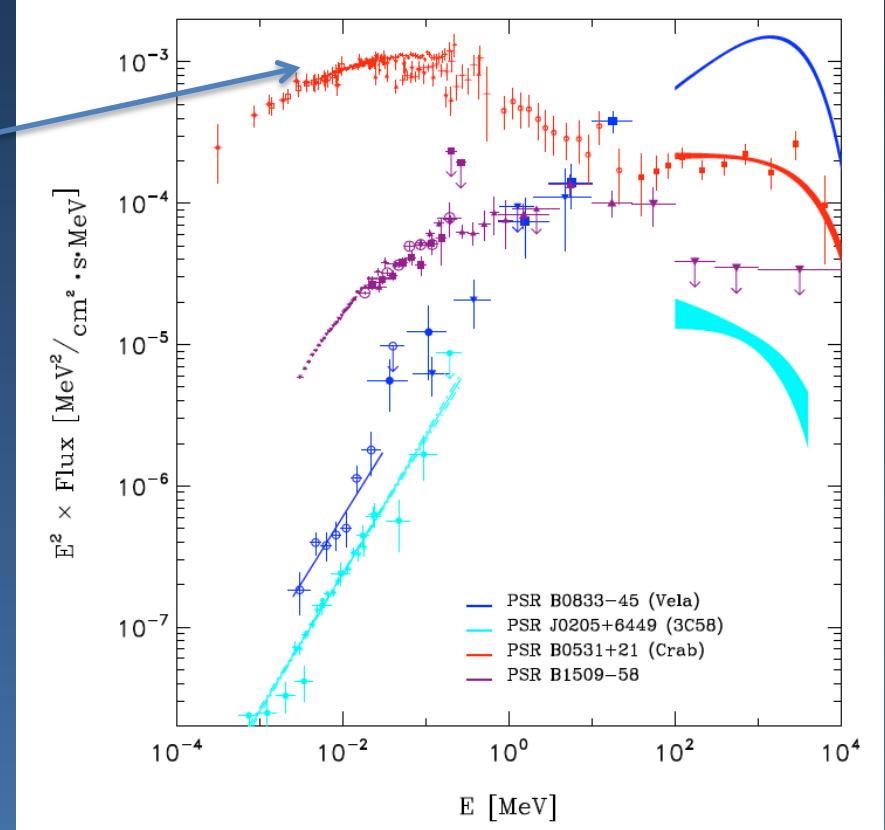
# VHE: Synchrotron self-Compton emission?

Essential ingredients: 1) Energetic particles  
2) High synchrotron emission level

Pair cascade spectrum (polar cap)



High-energy pulsar spectra

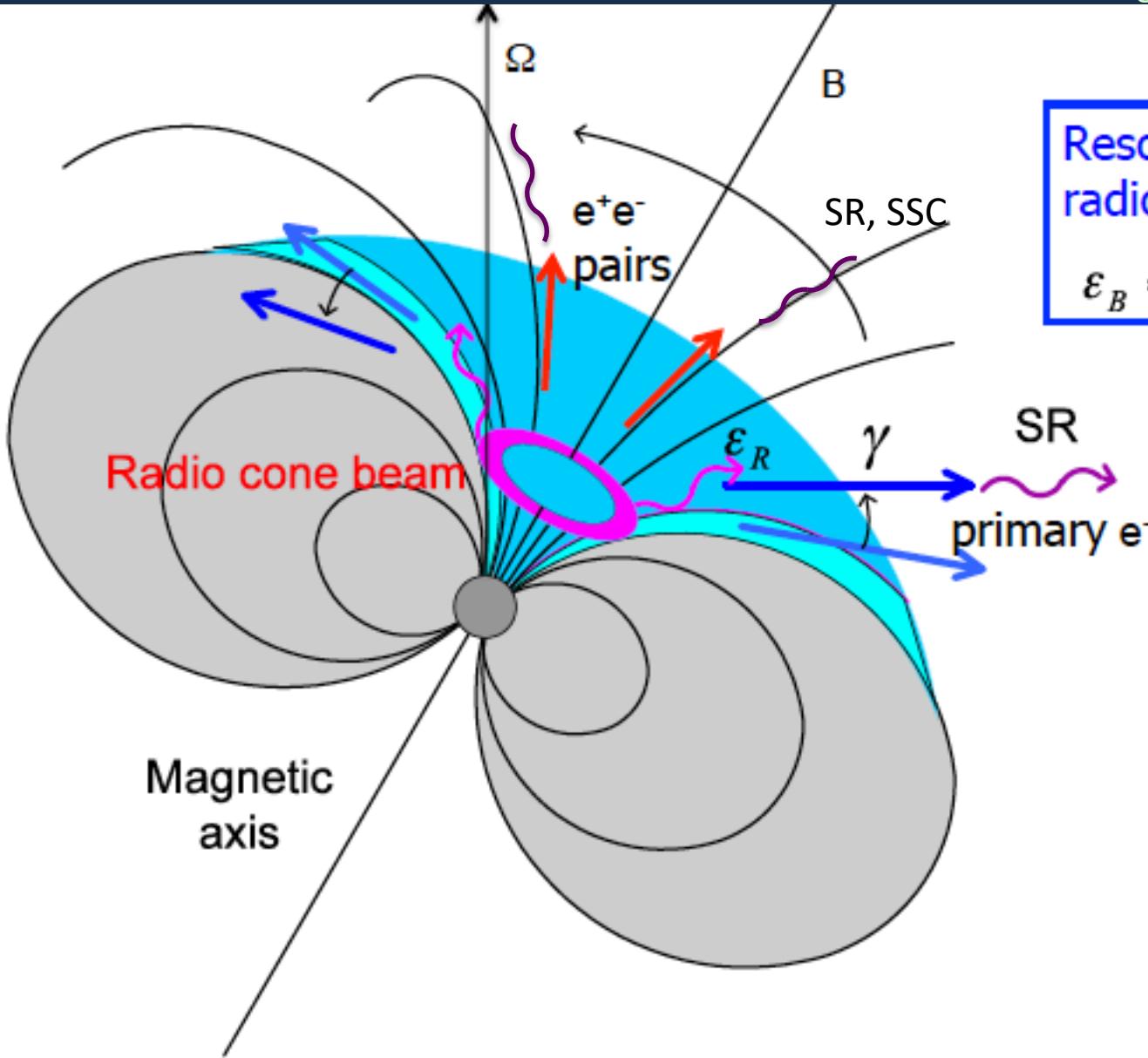


Energetic pair spectrum and high non-thermal X-rays produce high level of SSC

SSC emission from middle-aged pulsars will be much lower

# Simulation of SSC radiation

Harding & Kalapotharakos 2015



Resonant absorption of  
radio photons when

$$\varepsilon_B = \gamma \varepsilon_R (1 - \beta \cos \theta)$$

Petrova & Lybarski 1998  
Harding et al. 2008

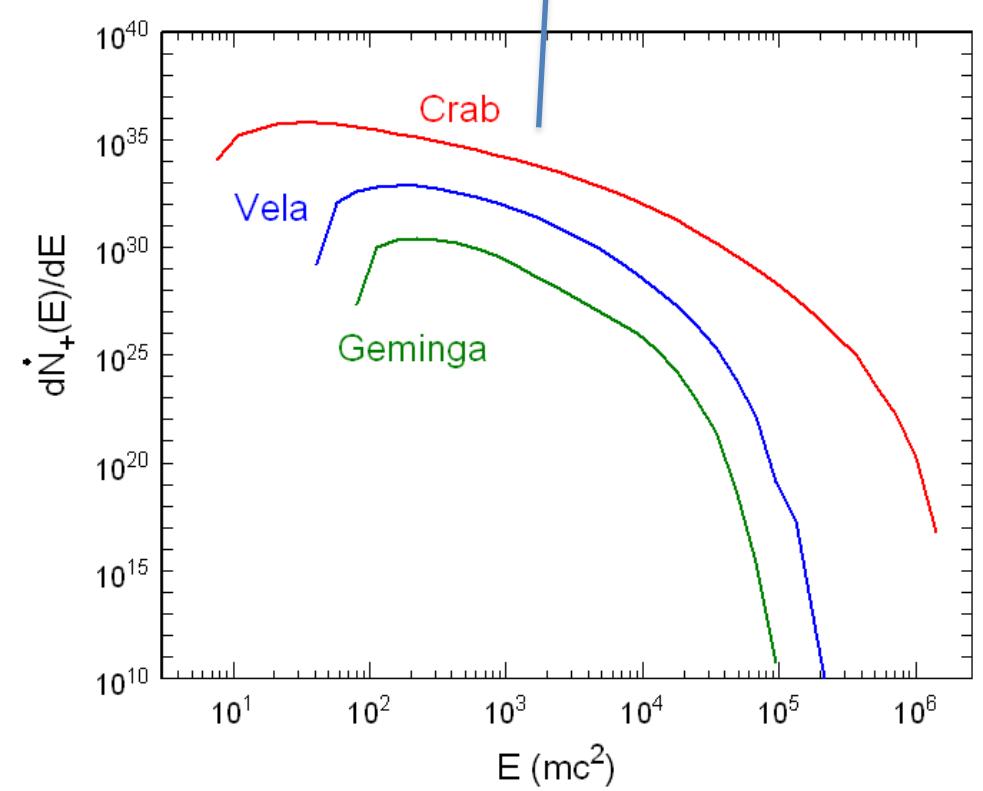
Force-free magnetic  
field

Acceleration and  
emission from NS  
surface to  $2 R_{LC}$

# Synchrotron self-Compton emission

$$\frac{dN(\varepsilon_s)}{d\varepsilon_s d\Omega_s} = c \int dE n_{\pm}(E) \int d\Omega \int d\varepsilon n_{\gamma}(\varepsilon, \Omega) \frac{d\sigma(\varepsilon' \Omega')}{d\varepsilon' d\Omega'} (1 - \beta \cos\theta)$$

Pair cascade spectrum (polar cap)



Synchrotron emissivity

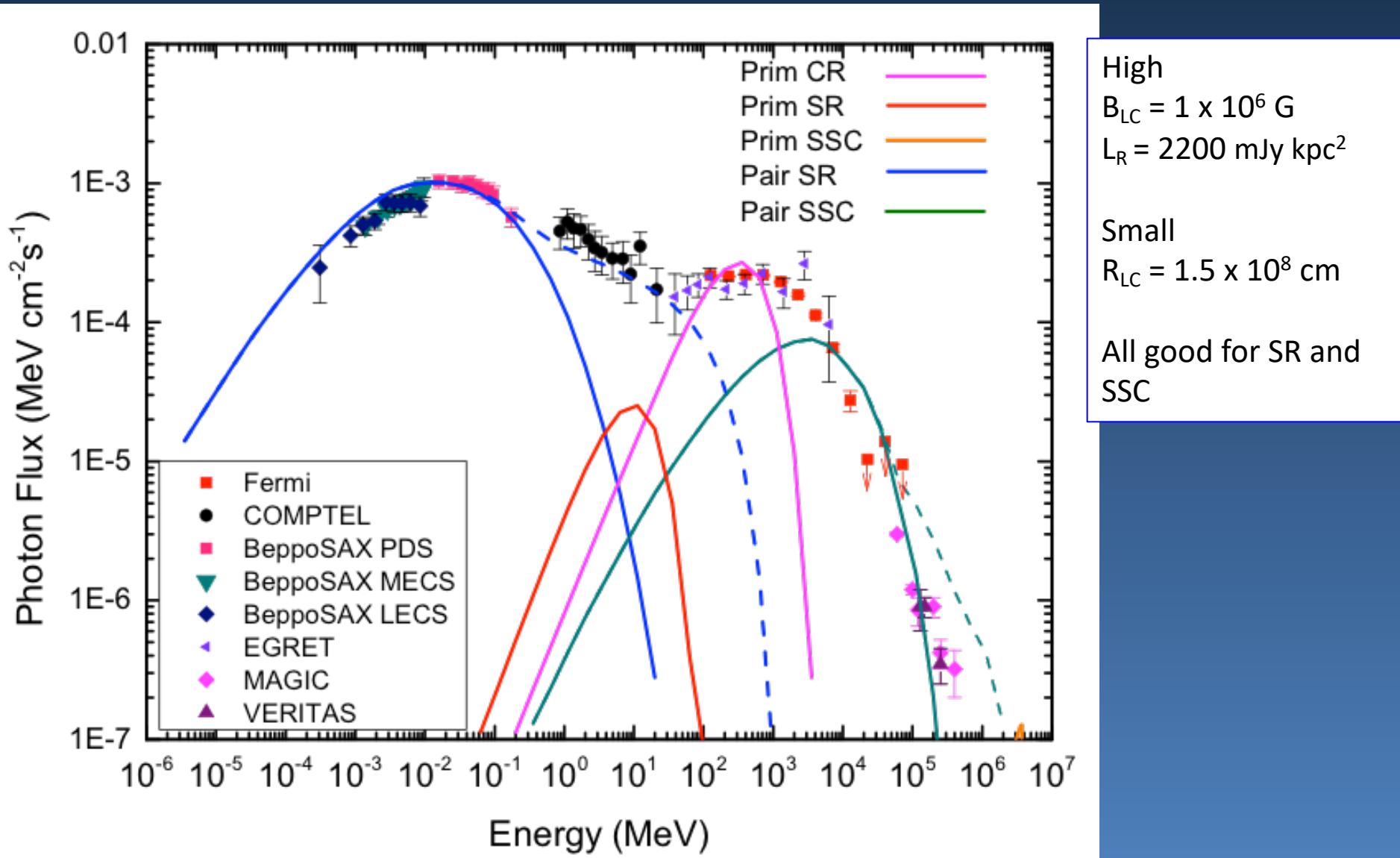
$$n_{\gamma}(\varepsilon, r, \Omega) = \frac{1}{c} \int dr_s \frac{\epsilon_{SR}(\varepsilon, r, \Omega)}{(r^2 - r_s^2)}$$

Synchrotron photon density

# SSC emission from Crab pulsar

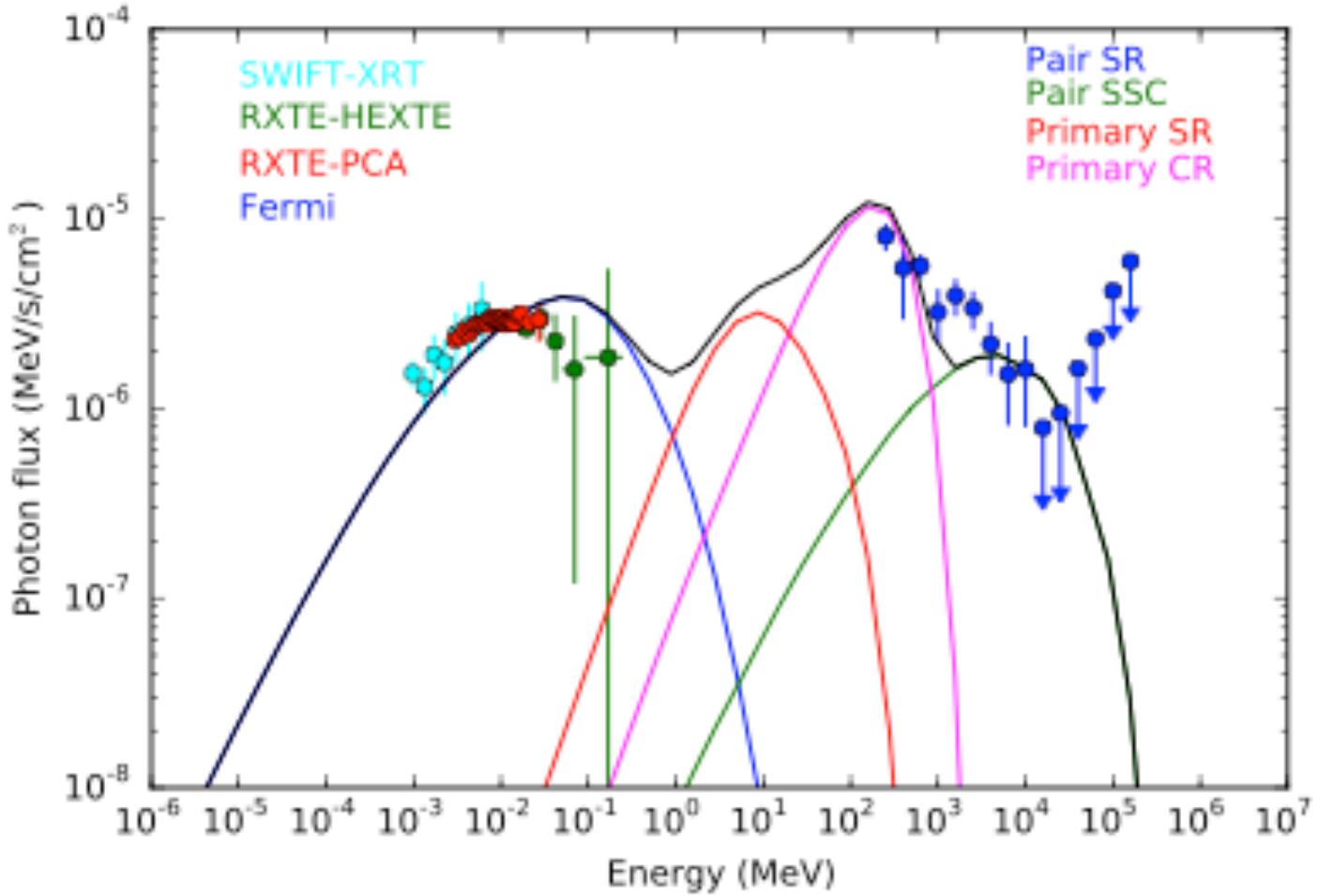
Harding & Kalapotharakos 2015

$$\alpha = 45^\circ, \zeta = 60^\circ, M_+ = 3 \times 10^5$$



# SSC from Crab-like pulsar B0540-69

$$\alpha = 45^\circ, \zeta = 70^\circ, M_+ = 3 \times 10^5$$



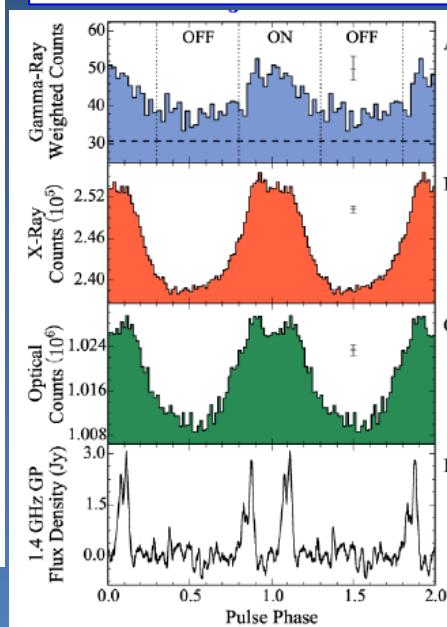
Fermi data – Ackermann et al. 2015

High  
 $B_{LC} = 3.6 \times 10^5$  G

Small  
 $R_{LC} = 1.5 \times 10^8$  cm

But  
 $L_R = 1000$  mJy kpc<sup>2</sup>

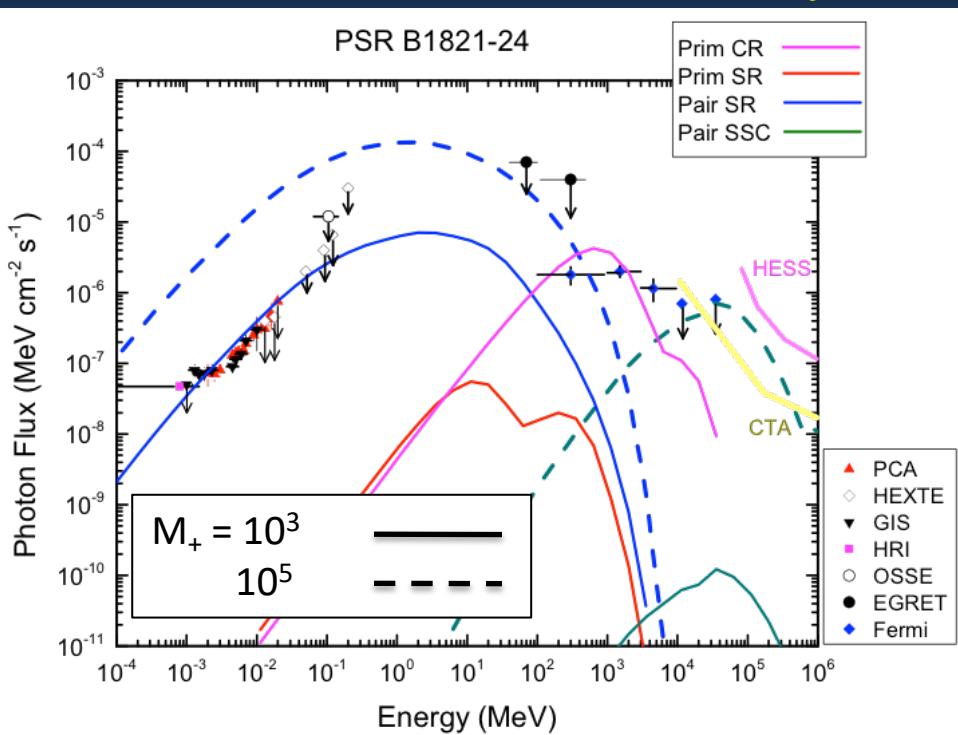
So, smaller SR and SSC



# SSC emission from MSPs

Harding & Kalapotharakos 2015

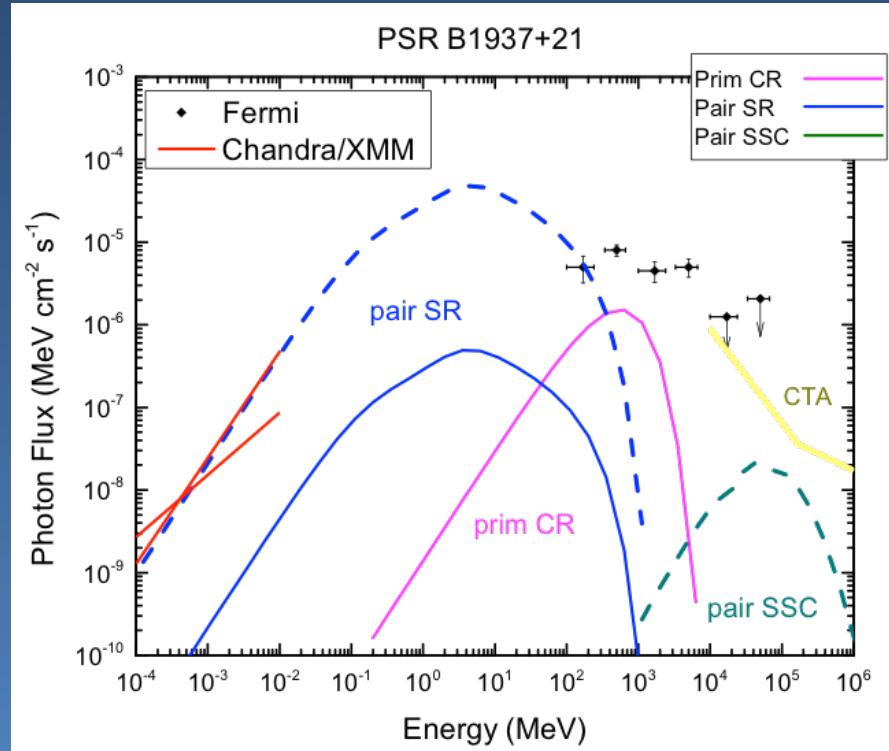
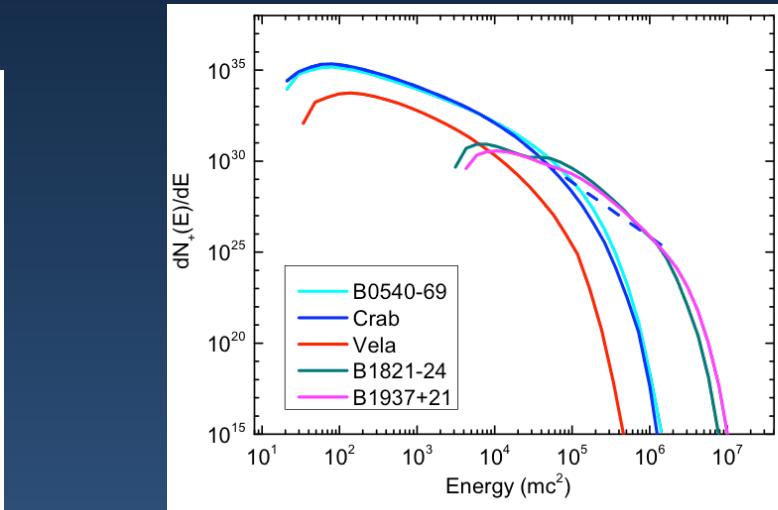
$$\alpha = 45^\circ, \zeta = 80^\circ$$



SR spectra peak  $\sim$ 1-10 MeV

SSC peak  $\sim$  100 GeV but lowered by KN reductions

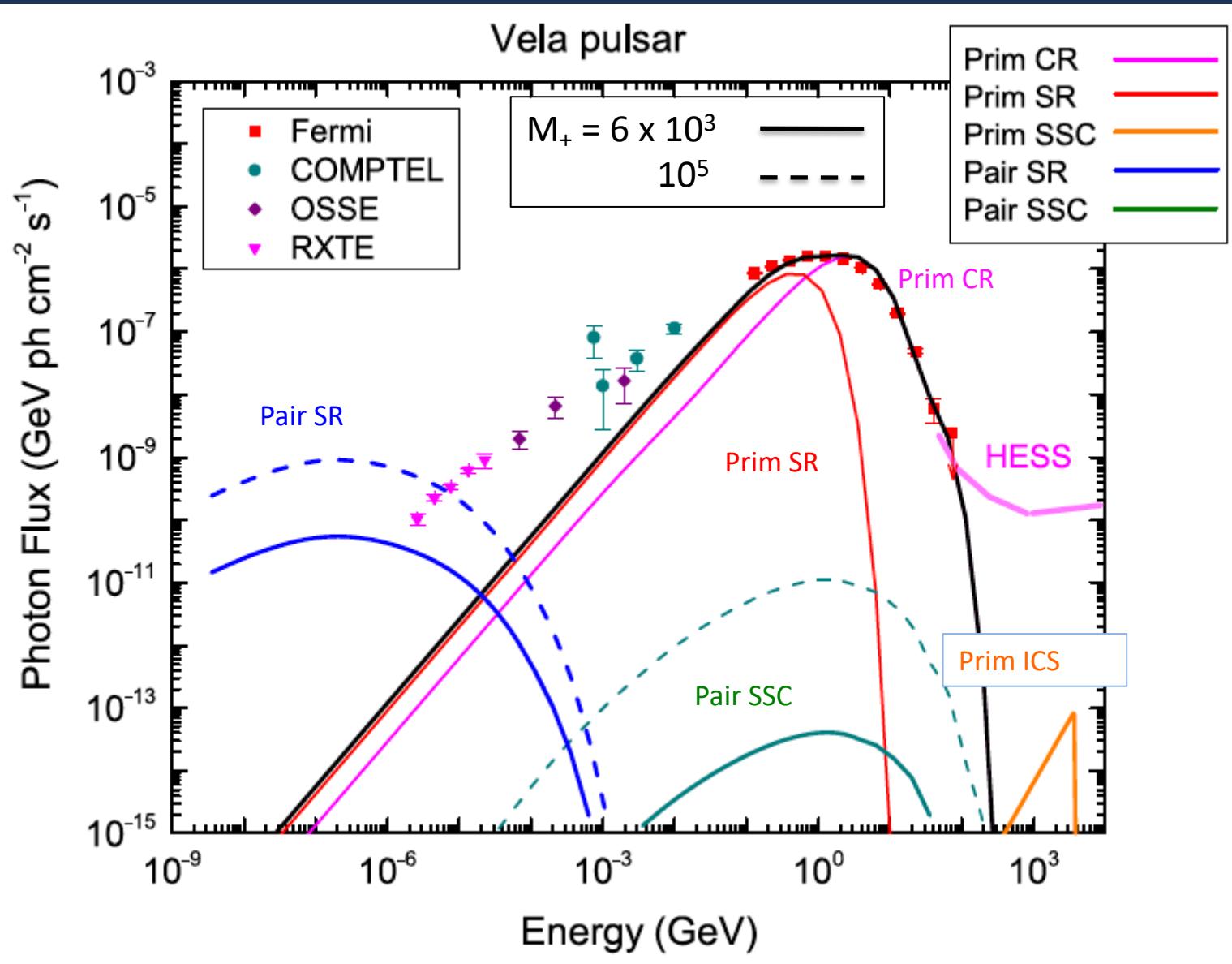
$$\alpha = 75^\circ, \zeta = 70^\circ$$



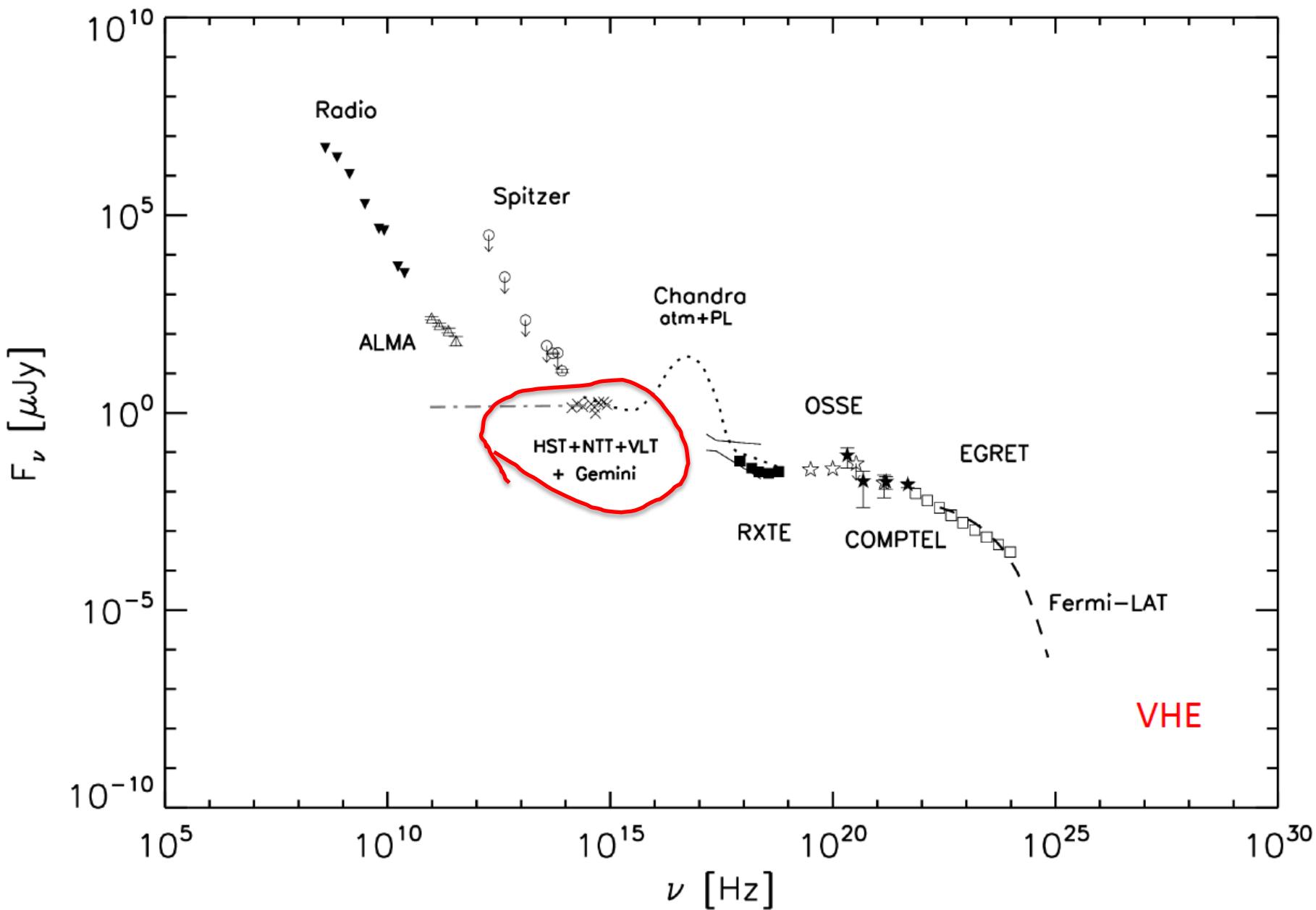
# SSC emission from Vela pulsar

Harding & Kalapotharakos 2015

$$\alpha = 75^\circ, \zeta = 60^\circ$$

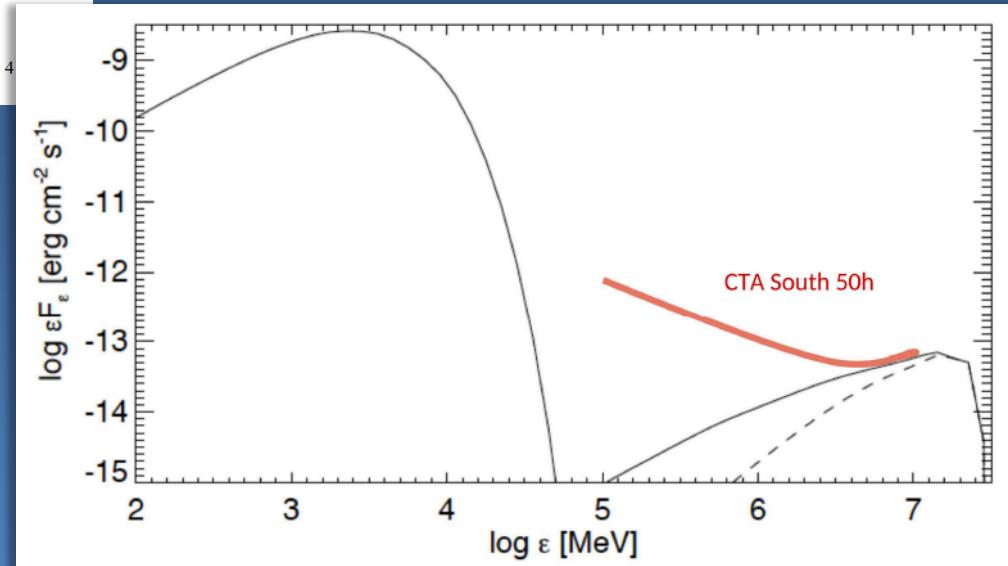
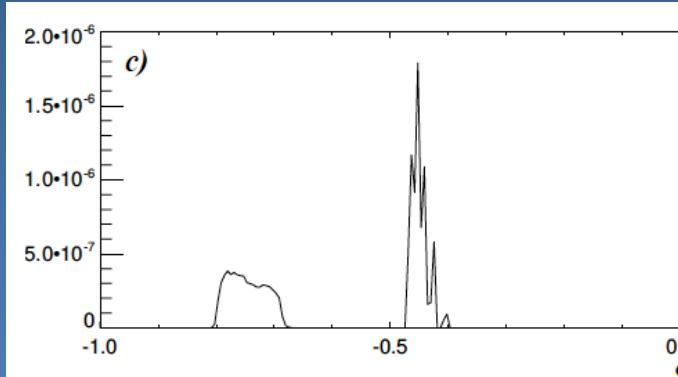
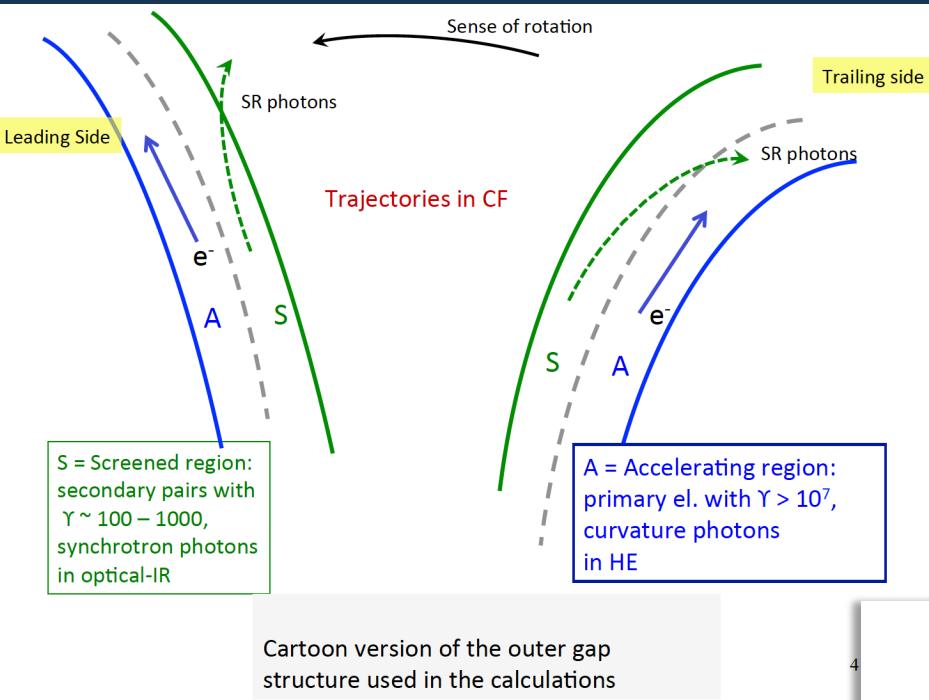


# Spectral energy distribution of the Vela pulsar



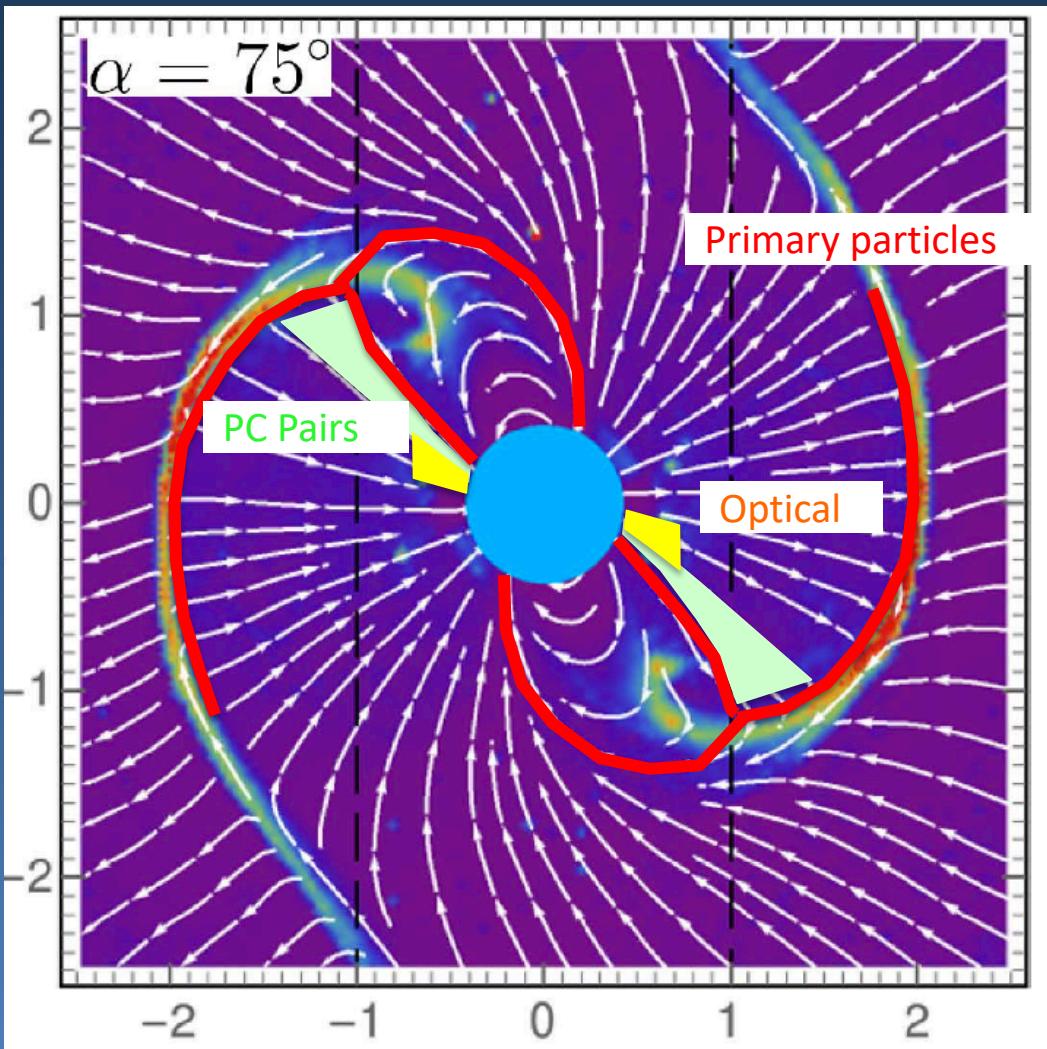
# ICS model for Vela TeV emision

Rudak & Dyks 2017



# Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018



Near force-free magnetosphere

- PC pairs produce SR optical/UV at lower altitude
- Primary particles (mostly positrons) produce synchro-curvature and scatter optical/UV to produce 10 TeV ICS emission
- Pairs scatter optical/UV to produce SSC hard X-ray emission

# Pair cascades vs. current

Sub-Goldreich-Julian  
currents –  $0 < J/J_{GJ} < 1$

NO pair cascades

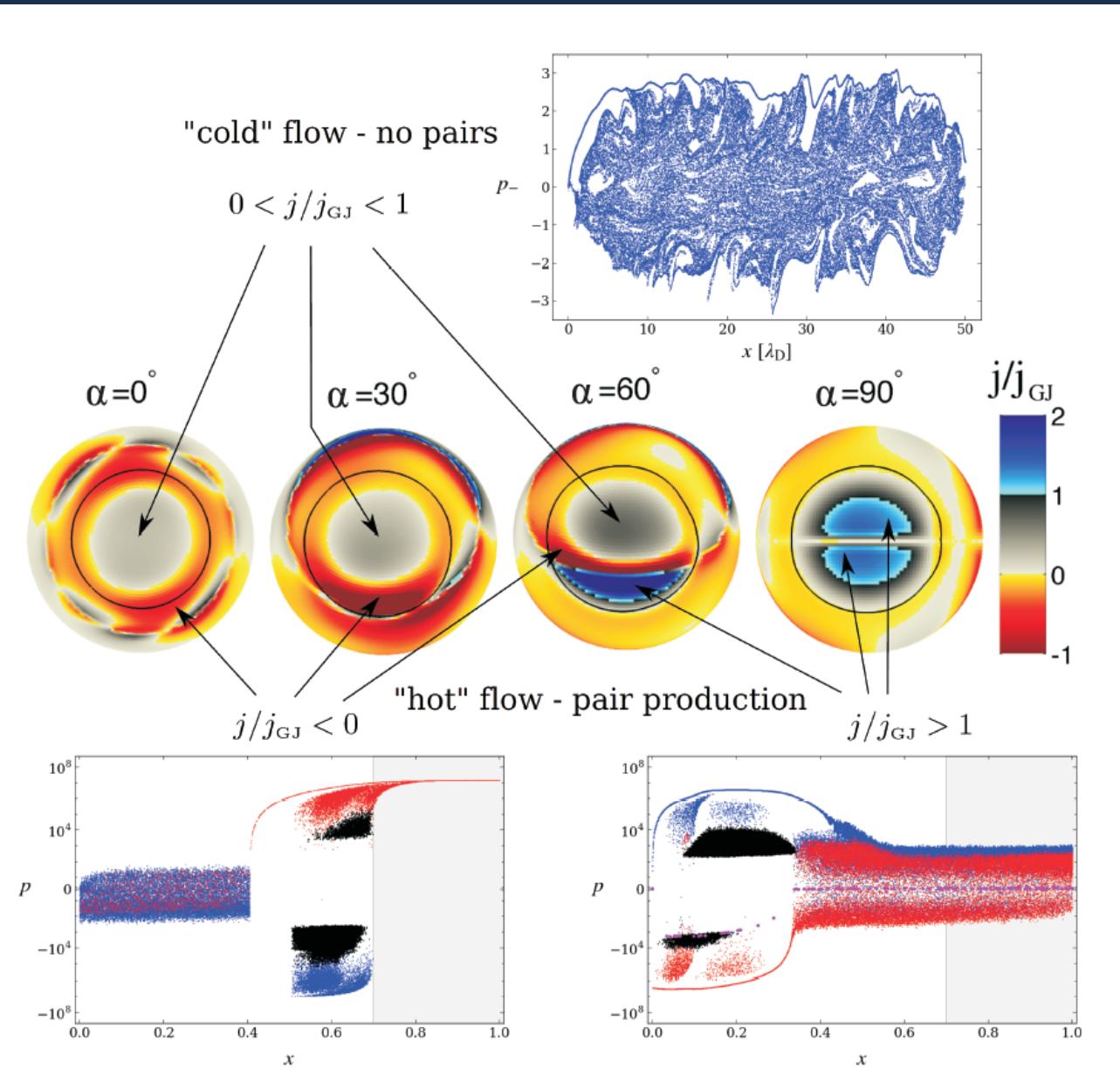
Super- Goldreich-  
Julian currents –  
 $J/J_{GJ} > 1$

Pair cascades

Anti-Goldreich-Julian  
currents -  $J/J_{GJ} > 0$

Pair cascades

Credit: Andrey Timokhin

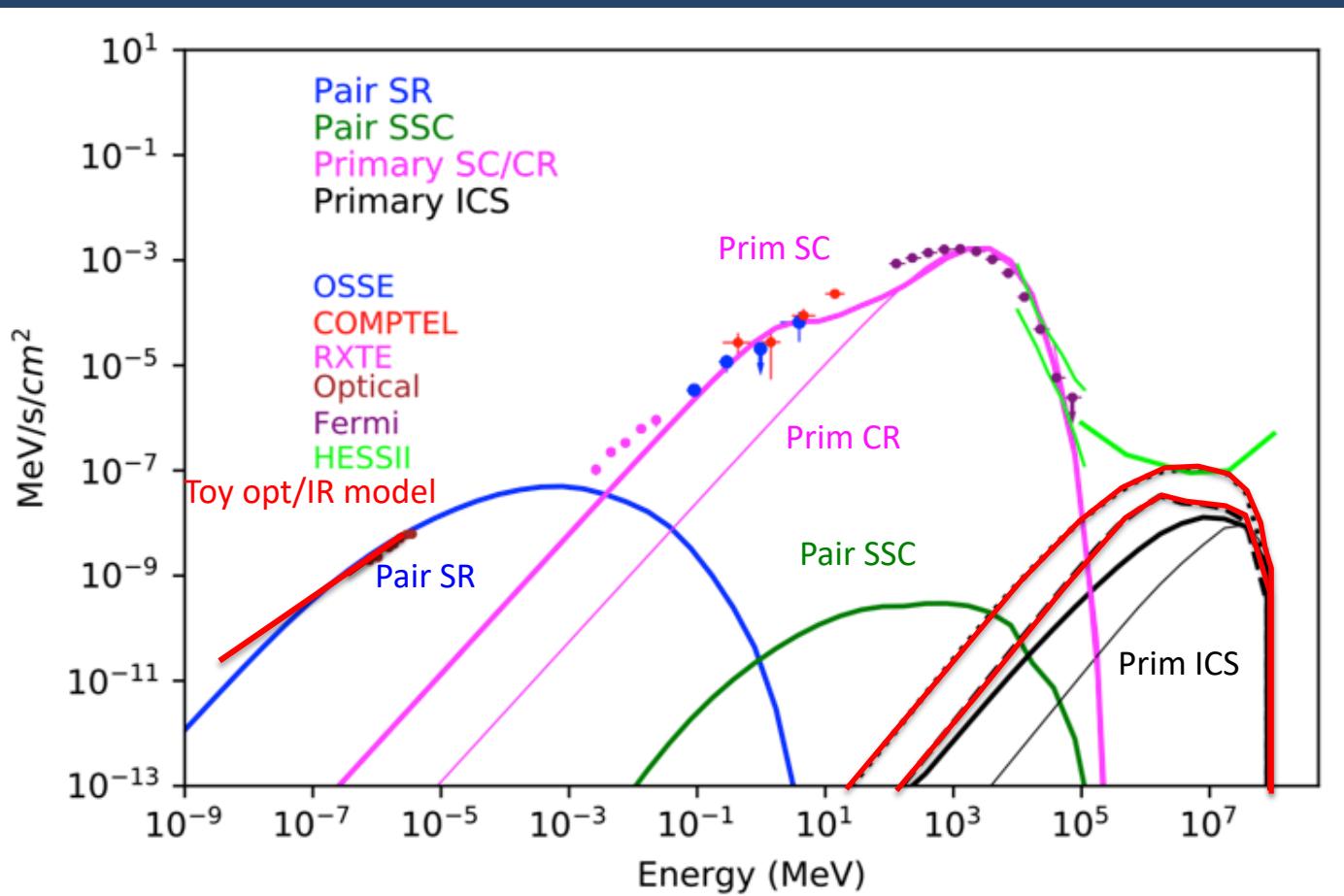


# Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018

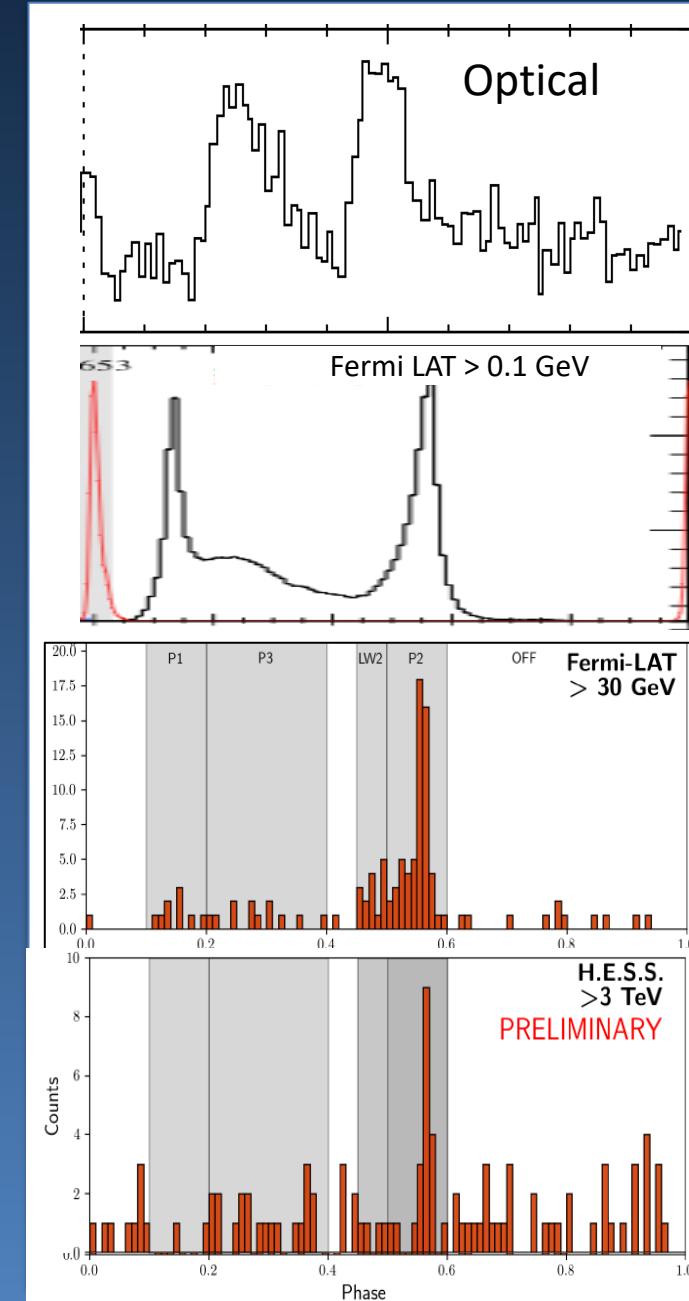
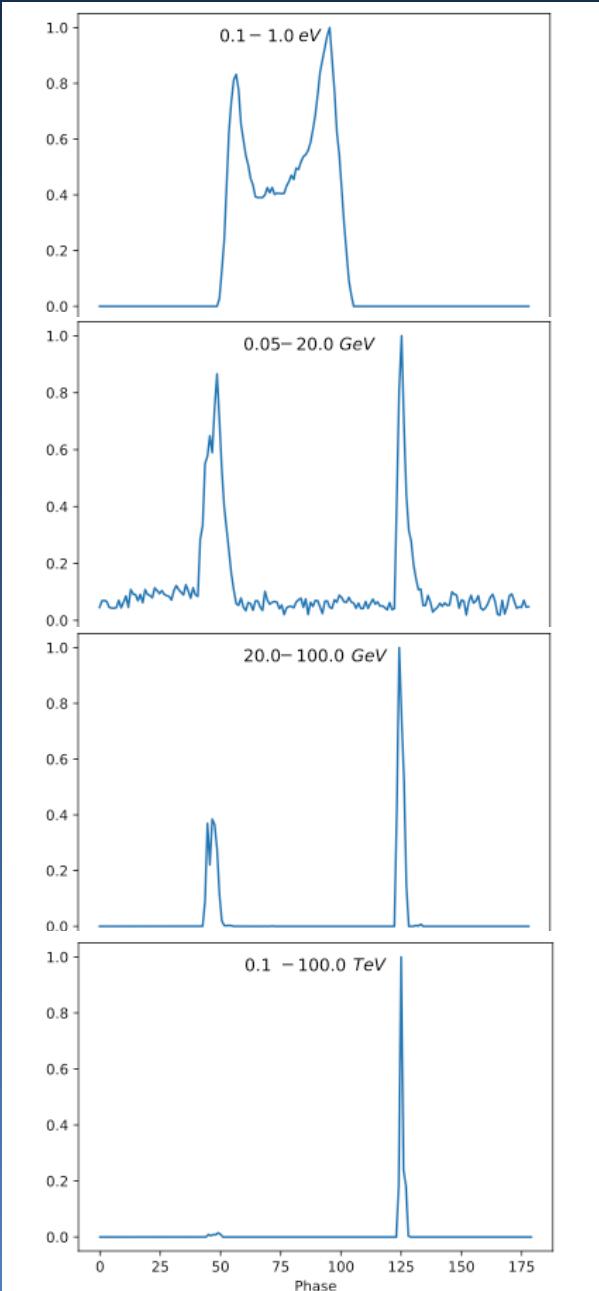
$$\alpha = 75, \zeta = 65, \text{pair } M_+ = 6 \times 10^3$$

- Detectable component from primary ICS around 10 TeV!
- Pair SR matches optical spectrum
- Primary ICS is really SSC



Pulsed emission at 10 TeV requires higher particle energy → GeV emission is CR

# Model light curves



Harding, Kalapotharakos,  
Venter & Barnard 2018

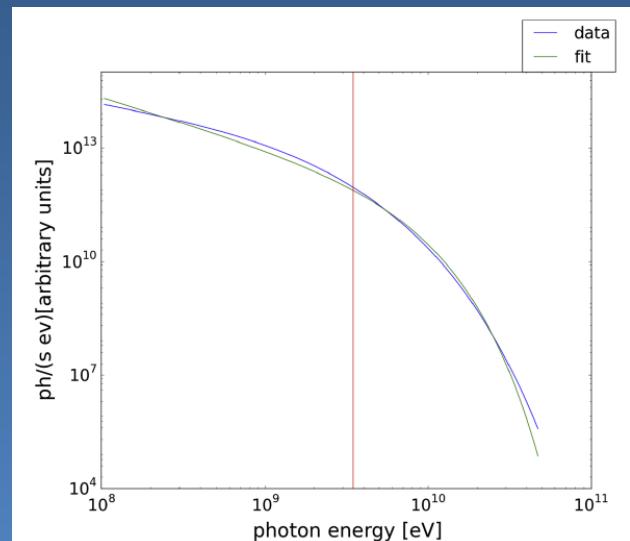
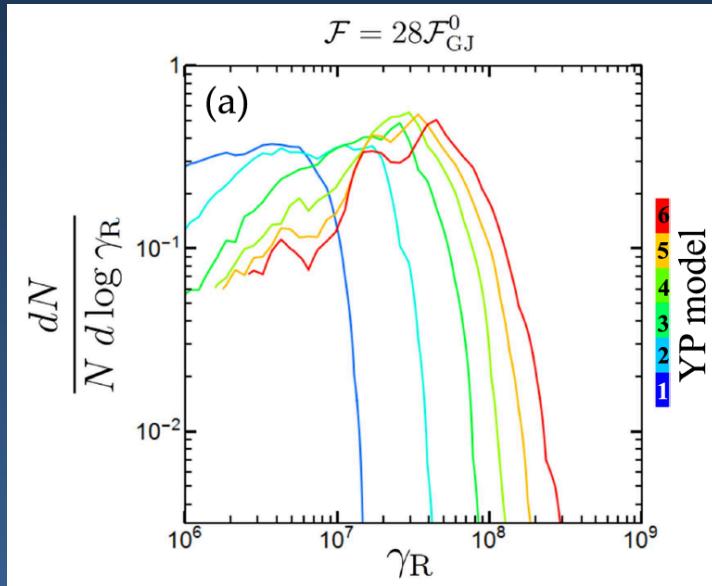
Fermi P2/P1 increases  
with energy – higher  $\gamma$   
particles produce P2

P2 only at > 3TeV –  
ICS from highest  $\gamma$   
particles

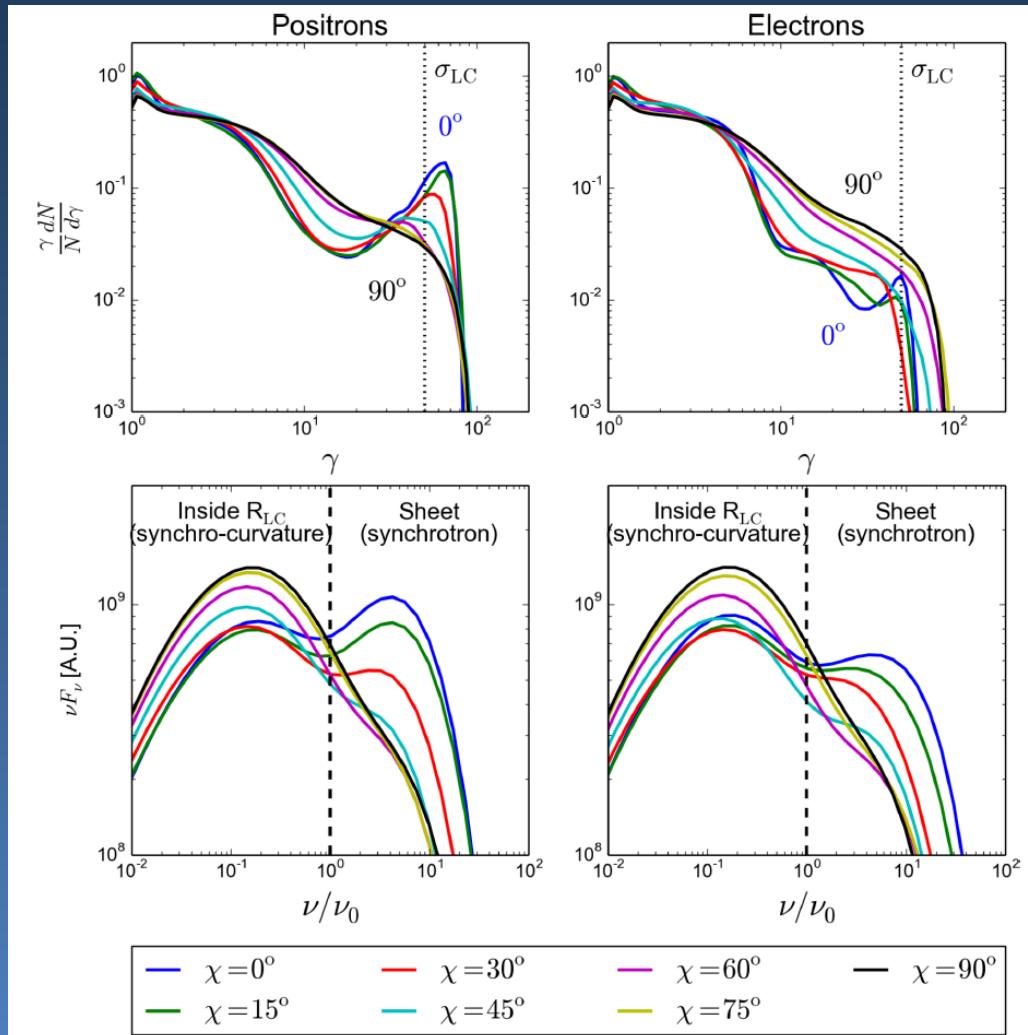
Large model  $\gamma$ -  
ray/radio phase lag  
due to azimuthally  
symmetric emission in  
current sheet

# GeV emission

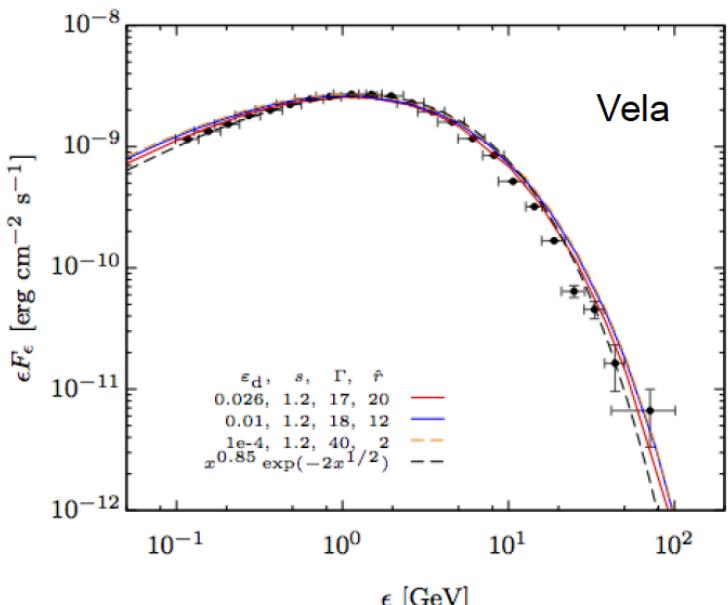
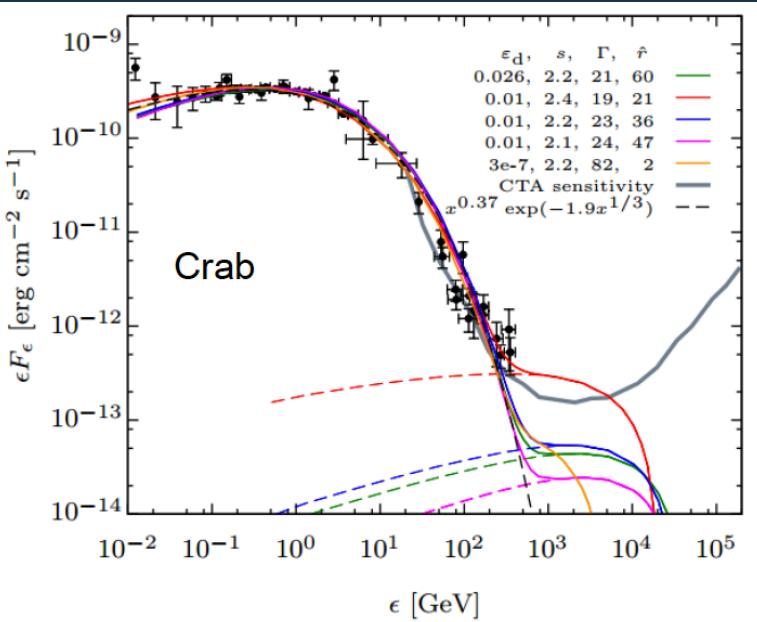
Curvature? (Kalapotharakos+  
2014,2017,2018)  $\gamma \sim 10^7\text{-}10^8$



or synchrotron? (Cerutti+ 2016, Philippov & Spitkovsky 2018)  $\gamma \sim 10^5\text{-}10^6$



# SR from current sheet



Mochol & Petri 2015

- GeV emission is SR from particles accelerated by magnetic reconnection in current sheet
- SSC component in Crab up to 3 TeV
- Particle  $\gamma \sim 3 \times 10^5$  so Doppler boost by wind  $\Gamma = 100$  required
- SSC component for Vela is orders of magnitude lower

# Summary and future prospects

- Fermi and ACTs are providing ground-breaking results
- SSC radiation from pairs can produce detectable emission for Crab-like pulsars and energetic MSPs
- IC radiation from most energetic particles scattering IR/Optical can produce VHE emission at highest particle energies ( $> 10$  TeV)
  - Need to model 18 orders of magnitude in photon energy!
- Unresolved questions
  - What is the GeV radiation mechanism (CR, SR, ICS)?  
10 TeV+ emission components clearly favor CR
  - Polarization measurements (HARPO, Adept)
  - What is the primary source(s) of pairs?  
MeV telescope (AMEGO)